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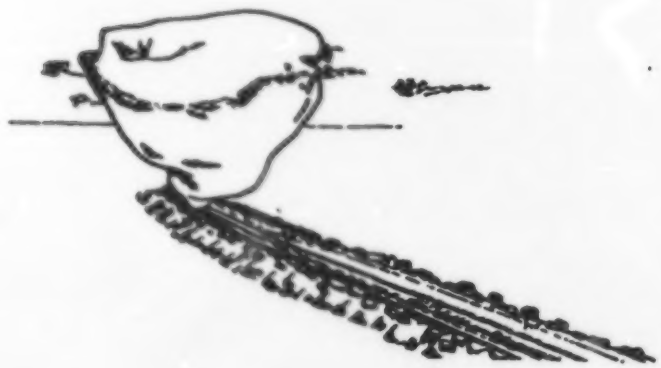

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OBSERVED DEFORMATION STRUCTURES BENEATH RELICT ICEBERG SCOURS

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ABSTRACT

Observation of sub-surface deformation structures beneath modern oceanic iceberg scours is impossible, but Quaternary scours exposed above sea or lake level on land provide this opportunity. Well developed iceberg scours which are clearly visible on the former bed of glacial Lake Agassiz in southeastern Manitoba were chosen for detailed studies of sub-scour deformation.

Partial burial of the scour troughs and the absence of bioturbation of the clay sediments have preserved the surface morphology and sub-scour deformation structures in pristine condition. Low angle faults and sub-horizontal thrust faults are developed below the scour trough, the former extending to at least 5.5 m beneath the deepest part of the scour incision surface. These faults formed in response to vertical and horizontal loading of the lakebed by the encroaching keel. In places, high angle normal faults developed outside the scour margin may represent gravity collapse of sediment blocks that were piled up on the scour berms as a result of lateral displacement of material away from the axis of the scour. Definition of deeply penetrating faults has significant engineering implications for the burial depths required to protect oil and gas production pipelines in areas of active scouring today.

INTRODUCTION

The keels of drifting icebergs or sea or lake ice pressure ridges which plough through seafloor or lacustrine sediments generate characteristic curvilinear furrows referred to as iceberg scours. A great deal is known about the surface morphology of scours, mostly from descriptions of sidescan sonograms and from visual examination of fresh scours from submarines. However, virtually no data exist on the nature and extent of sediment deformation beneath iceberg scours.

Presently on the eastern Canadian continental shelf curvilinear scours are formed by continuously moving icebergs which excavate characteristically flat-bottomed troughs. In the troughs of individual scours small scale, axis-parallel ridge and groove microtopography (up to 30 cm relief) is formed at the trailing edge of the scouring keel by boulders and cobbles embedded in the ice (Hodgson *et al.* 1988). Most of this is probably clastic seabed

material mechanically incorporated into the keel. Linear scour berms, which consist of "blocky" material up to 6 m high on either side of the trough, are characterized by a network of vertical columnar or radial fractures which extend downwards at least 1 m (Hodgson *et al.*, 1988). Similar structures have been observed along berm crests of fresh scours in the Beaufort Sea (e.g. Barnes and Reimnitz 1979).

Observations of surface features clearly suggest that deformation affects sediments to some depth beneath the seabed. However, documentation of these effects in terms of deformation structures is sparse (Fischbein 1987; Thomas and Connell 1985; Eyles and Clark 1988).

This paper describes in detail the cross-sectional morphology and subscour deformation structures associated with relict iceberg scours subaerially exposed on the floor of glacial Lake Agassiz in southern Manitoba, Canada.

LAKE AGASSIZ ICEBERG SCOURS

A region immediately southeast of Winnipeg was selected where prolific well-preserved exposed scours are preserved in thick clays of former glacial Lake Agassiz (Figure 1). The scours are partially buried beneath a 2-3 m thick layer of silty clay, thick enough to protect scoured sediments from the effects of farming activities and from deformation related to seasonal freeze/thaw of the ground. Four scours (A - D) were chosen for study from analysis of aerial photographs of the area (Figure 2). In the regions chosen for excavation each scour is relatively free from the influence of other scours.

METHODS

A bulldozer and backhoe were used to expose cross-sections of the scours to maximum excavated depths of 9 m. The contact between the scour surface and overlying infilling sediment was well defined in all scours (Figure 3). Block samples were taken from the sediments below scours A and B for the analysis of microstructures.

WATER DEPTH AND AGE OF SCOURS

Prior to scouring a period of subaerial exposure existed between about 10 300 and 9 900 years ago. By using estimated lake levels in the Lake Manitoba basin (Teller and Last, 1981) and from Lake Agassiz outlets to the east (Teller and Thorleifson, 1983) it is likely that the study area was exposed at least 7 m above lake level during this period. The interpretation of exposure and possible desiccation is supported by the results of a 1987 in situ geotechnical testing at scours A and B which indicates overconsolidation of the clays down to a consistent depth of 8 m below the present ground surface (Woodworth-Lynas and Landva, 1988).

About 9 900 years ago the eastern outlets were dammed by glacial ice, and lake depth increased to about 110 m (Teller and Thorleifson 1983). Woodworth-Lynas and Matile (1988) present evidence that the rise in lake levels at this time triggered a southeast-directed surge of ice from north of the Winnipeg area terminating east of the study area against a significant (unnamed) north-south oriented moraine. After the surge the ice sheet would have begun to disintegrate producing numerous icebergs which scoured the previously exposed lake bed sediments, beginning shortly after 9 900 years ago when water depths rose to about 110 m. In the study area deposition of a tan-coloured unit which fills the scour troughs was underway during the period of scouring because reworked sediments of the lowermost part of the unit are incorporated within deformed sediments of the underlying dark brown and grey clay unit at scours B and D (see below). As water depth increased beyond 60 m scouring by lake ice pressure ridge keels would not have occurred (e.g. Reimnitz *et al.* 1984).

GEOLOGY OF THE SCOURS

Scour A is about 50 m wide and can be traced for at least 6 km, both ends probably being obliterated beneath thickening sediments of the tan-coloured unit (Figure 2). Scour B is about 55 m wide as measured between berm crests exposed in the excavations, and can be traced for at least 8.5 km before dying out beneath overburden deposits at both ends. Scour C is about 65 m wide and can be traced for at least 6.5 km, and scour D, which is about 60 m wide, can be traced for only 0.5 km, both ends being obscured by other cross-cutting scours. It is stressed that scour width should be taken as an approximate measurement because in the excavations well-defined scour berms are not readily apparent. This is because the berms may have originally stood proud from the lakebed, and when lake levels fell to zero depth the berms may have experienced preferential subaerial erosion. Also, where the scour margins are very close to the ground surface, there has probably been additional reworking by seasonal freeze/thaw and agricultural tilling.

The scours are incised into brown and grey mottled clays (Figure 3), and sub-scour sediments at scours B and D also contain zones of reworked tan-coloured silty clay. The brown and grey clay is generally plastic with notable exceptions at scour A where discrete zones of brittle clay occur immediately below the incision surface. In these zones, which are 50 cm - 75 cm thick, the clay fractures and disaggregates when handled, in contrast to the plastic clay which is cohesive and easily sampled.

Except where it has been affected by scouring, the tan-coloured unit occurs as a well laminated deposit of silty clay filling the scour troughs. At scour B discrete horizons, generally less than 10 cm thick, of yellow/white finely cross-bedded silty clay occur.

SUB-SCOUR DEFORMATION STRUCTURES

Scour A.

Small scale kink folds are seen immediately below the incision surface on the southwest edge of the scour. The folds are sharp-crested and symmetric with flat limbs and vertical axial surfaces, and have amplitudes and wavelengths no greater than 5 cm. The scour incision surface has not been affected by the folds implying that the iceberg keel may have been in contact with the clay either during fold generation or immediately after they were formed so that they were truncated by the passing keel.

Unlike the other scours faults were not seen in any part of the section. In part this may be the result of the general absence of bedding, truncation and offset of which is an important criterion for identifying faults.

Scour B

Faults. In trench 1 a suite of symmetrically arranged faults affect the sub-scour clays (Figure 4). Faults are sometimes defined by offset bedding, but where bedding is absent they are hard to discern. After excavating the trenches minor settling sometimes caused small displacements (1-2 mm) of the trench walls along fault surfaces causing shadows to be thrown on the trench wall, thereby allowing their recognition in areas of structureless clay. Three types of fault are distinguished, each associated with different parts of the scour, and each related to different mechanisms of displacement during the scouring event. Fault types include I) deeply penetrating, low angle faults underneath the central part of the scour trough, II) sub-horizontal faults beneath the scour berms, and III) high angle faults located below the outer berm regions.

I. Low angle faults. On both sides of the scour between the inner berm flanks and the centre of the trough in trenches 1 and 2 a series of low angle faults dip towards the scour centre line at between 18° to 65°. In trench 1 the faults extend from the scour incision surface to at least 3 m below the deepest part of the scour trough. Excavation of the faults revealed well developed highly polished slickensided slip surfaces. Along the single low angle fault on the northeast side of the scour (Figure 4) a band of severely distorted clay laminae are truncated at the hanging wall (Figure 5). Continuity of this band is not seen on the hanging wall side suggesting dip slip displacement of at least 3.5 m along the fault. There is no distinct marker horizon associated with the anastomosing low angle faults on the southwest side of the scour so that relative amounts of displacement cannot be inferred. The sense of fault motion (normal or reversed) is not clear although apparent drag folds associated with the southwest fault set suggests reverse movement.

In places the low angle faults offset the scour incision surface by about 20 cm of normal displacement. Because the faults also extend into and offset laminated sediments of the overlying

tan-coloured unit by the same amount the movement is clearly a fault reactivation phenomenon of post-scour and post- early tan-coloured unit age.

Trench 2, 35 m beyond trench 1, was excavated to a depth of 5.5 m below the deepest part of the scour incision surface (depth below ground of 9 m). A set of low angle faults dipping towards the scour centre line was exposed. The fault on the northeast side of the scour was traced to at least 4.5 m below the scour trough (the bottom of the trench), and a double fault on the southwest side extended to at least 5.5 m below the scour trough. The faults on both sides were connected by a sub-horizontal fault at about 4 m below the scour trough. The sub-horizontal fault propagates from, and is continuous with, the low angle fault on the northeast side. Below the inflection point where the low angle fault becomes horizontal, two low angle offshoots continue downwards to the bottom of the trench.

On the southwest side where they intersect, the horizontal fault is offset by one of the two low angle faults. The sense of displacement is normal with a dip-slip component of 70 cm. Both of the low angle faults continue to at least the bottom of the trench, 5.5 m below the scour trough. On the southwest side of the scour (beyond the original scour berms?) beyond the low angle fault system four other low angle faults dip away from the scour trough. The angle of apparent dip (as measured on the trench wall) of each fault decreases progressively further away from the scour at 30^0, 25^0, 18^0 and 14^0 respectively. A similar low angle fault on the northeast side dips away from the scour at 34^0.

II. Sub-horizontal faults. In trench 1. sub-horizontal faults are developed at depths between 1 - 3 m below the scour berms (Figure 4). There are no physical links between these faults and the low angle faults, and slickensides were not seen on most of the excavated fault surfaces. Excavations of the northeast berm exposed a slab of brown and grey clay bounded on the top by the scour incision surface and on the bottom by a sub-horizontal fault (Figure 4). The block rests on severely contorted laminated silty clays of the tan-coloured unit. Structural stacking of older above younger sediments implies both vertical and horizontal components of movement. Three sub-horizontal faults, arranged one above the other, occur on the southwest scour margin, but there are no tan-coloured unit sediments beneath them.

In a similar position to the sub-horizontal faults in trench 1, discontinuous faults occur in trench 2 beyond the low angle faults on the southwest side. The faults have small apparent dips of between $5\text{-}10^0$ to the southwest.

III. High angle faults. In trench 1. sediments beneath both outer berms contain high angle normal faults. Slickensides were developed on some fault surfaces. On the northeast scour margin normal faults offset a block of brown and grey clay, the horizontal base of which rests above distorted tan-coloured unit sediments on the outer berm (Figure 4). The faults do not affect the overlying tan-coloured unit. Faulting thus occurred before deposition of the

overlying unit, and suggests displacement soon after, or at the time of, scouring.

High angle faults with low angle offshoots are found below the outer berm on the southwest scour margin. The high angle faults are probably related to normal faulting although offset cannot be determined, the low angle offshoots possibly representing sub-horizontal fault contacts between clay blocks.

Folds and cleavage

Pre-scour primary bedding below scours B, C and D has been largely obliterated by mechanical disruption during scouring. At scour A. bedding in the scoured sediments is absent except where preserved in small scale kink folds (described earlier) in a very small region (few tens of cm^2) immediately below the incision surface.

Below scour B discontinuous laminations can be traced over small distances but are generally confined to fold structures. Dislocated small scale (5 -20 cm), disharmonic, non-cylindrical folds typify the brown and grey clay and incorporated tan-coloured unit sediments (Figure 6). Folds range from open, tight to isoclinal and there is no consistency in fold symmetry even between adjacent structures (see Figure 6).

Some folds are characterized by the presence of a well developed but non-fissile fracture cleavage. Cleavage planes are spaced about 1 mm apart with average displacements of 1 mm along the planes (Figure 7). Because they are associated with disharmonic folds there is no consistency in apparent cleavage orientation although it may be axial planar to specific folds. In places the cleavage is also folded. The cleavage is seen only in association with the folds and cannot be traced into the structureless groundmass.

Scour C

Sediments below scour C are typified by the occurrence of numerous unconnected fault segments often no greater than 0.5 m long (Figure 8). A low angle fault on the southwest side dips away from the scour trough at an apparent angle of 40^0, becoming less steep near the bottom of the trench. Beyond this fault are two semi-circular faults with apparent dips of about 55^0 towards the scour trough. One of these two faults recurves to dip away from the trough at a similar angle.

A possible set of low angle faults, similar to the set exposed below scour B, occurs on either side of the deepest part of the scour trough. These dip towards the scour centre line at apparent angles of 35^0 and 70^0 on the southwest side, and at 40^0 on the northeast side. However, the interpretation of the faults as part of a low angle set cannot be verified because the trench excavations only went 1.5 m below the deepest part of the scour trough. The faults extend below this depth.

Scour D

Below scour D undeformed horizontal layering is preserved between 1 and 1.5 m below the scour incision surface (Figure 9). The undeformed layering occurs in two zones, each approximately 8 m long on either side of the centre of the scour trough. Between the undeformed layering zones a large sub-horizontal lens of reworked tan-coloured silt 5 m long and 0.75 m thick, has been structurally emplaced along a sub-horizontal fault. A similar 3 m long lens of reworked tan-coloured silt occurs in the vicinity of the southwest berm. The upper surfaces of the two silt lenses are at approximately the same depth (1.5 m) below the incision surface as the undeformed layering.

Few continuous faults occur below the scour incision surface, and these do not conform to the well defined pattern observed at scour B. Notably two low angle faults are developed on the southwest side between the two lenses of tan-coloured silt. The faults propagate from the incision surface dipping towards each other, and almost intersecting, with apparent dips of 20^0 and 35^0. Other faults do occur in segments up to 2 m long, and most of these have low apparent dip angles. The scour was excavated to a maximum depth of 2.5 m below the deepest part of the trough, and the deepest fault is 2 m below the deepest part.

STRUCTURAL DATA

Stereoplots of fault surface attitude and slickenside orientation show similar structural geometries for scours B, C and D (Figures 10a, 10b, 11 & 12). There are no structural data from scour A because faults were not observed. Although there is some spread the diagrams show a general clustering of fault surface attitudes in all scours at approximately 55^0. The poles to these surfaces roughly plot in incomplete small circle fabrics (indicated by the domains drawn around the points) with a locus centred at the centre of the diagram in all cases. The consistency in structural symmetry between the scours implies similarity in origin. Fault structures below scour B are well exposed in two deep excavations, and their geometry may be similar to that in the other, less deeply excavated scours. A description of the scour B geometries might then be appropriate as a paradigm to explain the other scour geometries and structure.

In trench 1, scour B, the low angle faults (dipping towards the scour centreline) are symmetrically disposed about the scour axis within two distinct domains (Figure 10a). The spread of points parallel to the scour axis suggests an overall cusp - shaped fault geometry, the general attitude of the faults being slightly oblique to the axis. Slickenside data, also falling into two domains on either side of the scour axis (Figure 10a), are consistent with a sense of displacement symmetrically oblique to the scour axis. Tight clustering of horizontal fault plane data (collected solely from the southwest margin) indicate consistent fault attitude (Figure 10a), and high angle fault plane orientations are widely spread (Figure 10a). In trench 2 more orientation data were collected, and although the domainal nature

of the low angle faults is still apparent the domains more clearly define a partial small circle (dotted line). Other faults fall on, and complete, this circle.

Scour C shows spread in a small circle but with strong clustering of all fault plane data in two domains which are obliquely symmetrical to the scour axis. Although there are less data from scour D, the low angle faults dipping towards and away from the scour centreline are spread in a similar small circle.

INTERPRETATION

Poorooshasb *et al.* (1989) in their analysis of model scour tests, and of data collected from scour B, suggest that loading of the lakebed by the scouring keel caused shallow bearing capacity failure in the sub-keel sediments whereby a triangular-shaped wedge of material, bounded by the low angle faults which dip towards the scour axis and the scour incision surface, is displaced downwards (zone I of Terzaghi, 1959). The interpretation of Poorooshasb *et al.* (1989) indicated a normal sense of fault motion along the low angle faults (Figure 13) implying the continuation of the faults well below the depth of excavations. Extrapolation of the faults at constant angle shows that they would intersect at a point about 6 m and 10 m below the deepest part of the scour incision surface in trench 1 and trench 2 respectively. In the bearing capacity failure model two zones of radial shear (zone II of Terzaghi, 1959) are developed on either side of the passive zone which are displaced outwards along basal log spiral faults (Figure 13). Beyond these occur two triangular-shaped passive Rankine zones (zone III of Terzaghi, 1959) which are displaced upwards and outwards. In trench 2, scour B, the Rankine zone on the southwest side is characterized by a series of low angle faults with progressively shallower dips further from the scour. Such a geometry may be initiated by collapse along discrete failure planes of material in response to the upward movement of the zone. Fault motion would thus be normal.

The sub-horizontal block of brown and grey clay exposed on the northeast side of scour B, trench 1, may have originated from a structurally lower region near the centre of the scour. Horizontal forces of the encroaching iceberg keel caused decoupling of the block along a decollement within the brown and grey clay. Upward and outward translation of the "rigid" block occurred as the keel passed. The block overrode reworked sediments of the tan-coloured unit during final emplacement.

Although there is no direct evidence to indicate the direction of movement, the development of sub-horizontal faults beneath the scour margins in trench 1, scour B, suggests the sequential structural stacking of horizontal thrust blocks of brown and grey clay displaced from the central part of the scour by the scouring keel. Such stacking is envisaged as being responsible for generating positive relief of the scour berms.

High angle faults in trench 1, scour B, have variable orientations suggesting that fault formation is not directly related to stresses caused by the passing of the scouring iceberg keel. The faults are interpreted to have formed in response to gravity collapse of the outer scour berms which had an initial relief greater than present. The low angle offshoot faults associated with high angle faults on the southwest berm and the horizontal base of the clay block on the northeast berm originally may have been sub-horizontal faults related to the lateral thrusting of clay slabs now preserved below the inner scour margin.

Below scour D the two zones of undeformed, horizontal sedimentary stratification on either side of the scour centreline are anomalous, and similar regions do not occur below the other scours. The presence of two sub-horizontal lenses of tan-coloured silt at 1.5 m depth suggests that the silt has been structurally incorporated in the matrix of the brown and grey mottled clay. By analogy with reworked tan-coloured silt lenses below scour B it is possible that a large, continuous slab of brown and grey clay 1.5 m thick and possibly containing undeformed layering was thrust horizontally above early deposits of tan-coloured silt. However, except for a discrete sub-horizontal fault beneath the silt lens in the centre of the scour, a continuous thrust fault at this depth is nowhere evident.

Although not yet understood the structural geometry of all faults beneath scours B-D is consistent: all faults plot in a small circle centred in the middle of the stereoplots indicating dips of approximately 55^0 and faults display domainal clustering.

DISCUSSION

Deformation structures below scour A are sparse whilst scour-related deformation structures are prolific below scours B, C and D. This contrast is probably due in part to the almost total lack of bedding structures below scour A. As a result folding and faulting, which may well be present, cannot be defined in the unstratified groundmass. It is also possible that deformation structures, particularly faults, may develop as discontinuous features below scour troughs and that excavations at scour A did not intersect a faulted region.

The hypothesis of shallow bearing capacity failure as a scouring mechanism advanced by Poorooshasb *et al.* (1989) is compatible with some of the major observed sub-scour structures. Their interpretation satisfies the geometry of structures as observed in the two dimensions of the trench face. Further, it implies that for a large-based ice keel the size of zone *I* (Fig. 13) will increase, and correspondingly the slip surfaces beneath wider scours will penetrate deeper than below narrow scours. Poorooshasb *et al.* (1989) do not attempt to explain the geometry in three dimensions, nor account for other structures such as the sub-horizontal faults. The displacements accommodated along the low angle faults (between zones *I* and *II*, Fig.13) may be on the order

of 3.5 m. Such large movements bring into question the ability of buried pipelines to withstand such differential soil displacements.

Sub-horizontal faults below the scour marçins in trench 1, scour B, can be attributed to thrusting mechanisms directly related to horizontal translation of the iceberg keel through the seabed. Thrusting may also account for the zones of undisturbed layering and incorporation of lenses of tan-coloured silt below scour D. The horizontal fault joining the low angle faults beneath the centre of scour B, trench 2, also implies horizontal translation. The sub-horizontal fault is offset by the low angle faults on the southwest side indicating that the sub-horizontal fault developed first. This is a logical sequence because horizontal translation ahead of the keel would be expected to affect the sediment prior to arrival of the iceberg which then induces bearing capacity failure. The normal sense of offset of the sub-horizontal fault lends additional support to the bearing capacity mechanism. If the sub-horizontal fault developed ahead of the keel, and is related to forward horizontal translation, then the depth to which shear forces were propagated may have been as great as approximately 3 m as measured from the deepest part of the scour tough.

Sub-scour faulting may occur to depths of at least 5.5 m below the depth of incision (scour B), and other deformation structures occur to this depth also. The documentation of sub-scour effects to these depths suggests that modern scouring in fine-grained seabed sediments will have similar effects. Clearly then the imposed strains on buried oil and gas pipelines resulting from large (3.5 m+) offsets along scour-related faults need to be assessed. If the imposed forces are unacceptable it may require that pipelines be buried deeper than is presently planned in areas of active scouring. This is a very important consideration because incremental increases in pipeline burial depth will substantially increase the cost of installation. Thus acceptable pipeline loads and pipeline burial depth will have to be reconciled.

ACKNOWLEDGEMENTS

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REFERENCES

Eyles, N. and Clark, B.M. 1988. Storm-dominated deltas and ice-scouring in a Late Pleistocene glacial lake. Geological Society of America Bulletin, 100: 793-809.

Fischbein, S.A. 1987. Analysis and interpretation of ice-deformed sediments from Harrison Bay, Alaska. Unpublished M.Sc. thesis, California State University, Hayward, 107p.

Hodgson, G.J., Lever, J.H., Woodworth-Lynas, C.M.T. and Lewis, C.F.M. (editors). 1988. The dynamics of iceberg grounding and scouring (DIGS) experiment and repetitive mapping of the eastern Canadian continental shelf. Environmental Studies Research Funds Report No. 094, Ottawa, 318p.

Poorooshasb, F., Clark, J.I. and Woodworth-Lynas, C.M.T. Small scale modelling of iceberg scouring of the seabed. In Tenth International Conference on Port and Ocean Engineering under Arctic Conditions (POAC '89), Lulea, Sweden, 1: 133-145.

Reimnitz E., Barnes P.W. and Phillips, R.L. 1984. Geological evidence for 60 meter deep pressure-ridge keels in the Arctic Ocean. IAHR Symposium, Hamburg, 18p.

Teller J.T. and Last, W.M. 1981. Late Quaternary history of Lake Manitoba, Canada. Quaternary Research, 16: 97-116.

Teller J.T. and Thorleifson, H. 1983. The Lake Agassiz - Superior connection. In: Glacial Lake Agassiz (J.T. Teller and L. Clayton, eds.), Geological Association of Canada Special Paper 26: 261-290.

Terzaghi, K. 1959. Theoretical soil mechanics. John Wiley & Sons, New York (9th printing): 510p.

Thomas, G.S.P. and Connell, R.J. 1985. Iceberg drop, dump and grounding structures from Pleistocene glacio-lacustrine sediments, Scotland. Journal of Sedimentary Petrology, 55(2): 243-249.

Woodworth-Lynas, C.M.T. and Matile, G.L.D. 1988. Large scale linear ridge and groove topography from glacial Lake Agassiz and Hudson Strait: possible evidence for buoyant, surging ice sheets. In: Program with abstracts, Joint Annual Meeting, Geological Association of Canada, Mineralogical Association of Canada and the Canadian Society of Petroleum Geologists, Memorial *University of Newfoundland, St. John's, May 23-25: A137.

Woodworth-Lynas, C.M.T and Landva, J. 1988. Sediment deformation by ice scour. Contract report for Supply and Services Canada, 36p.

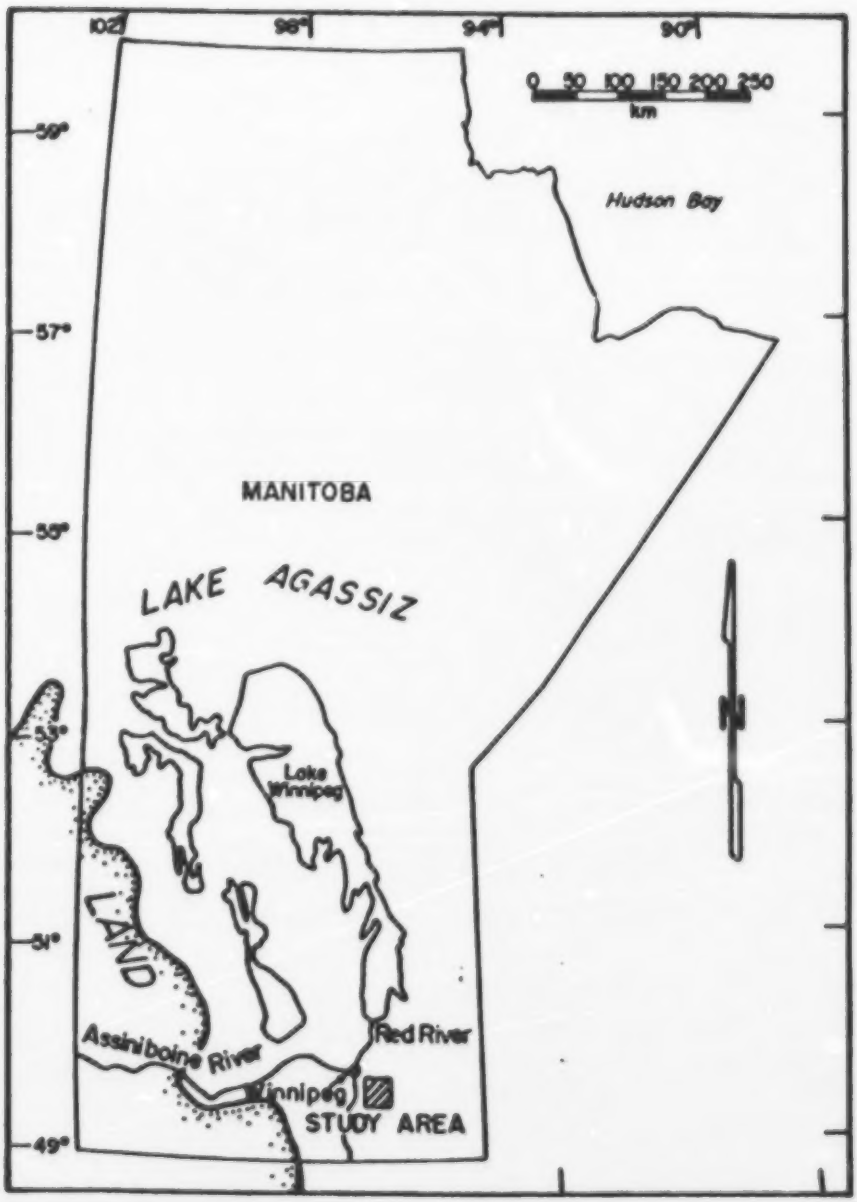

Figure 1. Location map of the study area in southeastern Manitoba.

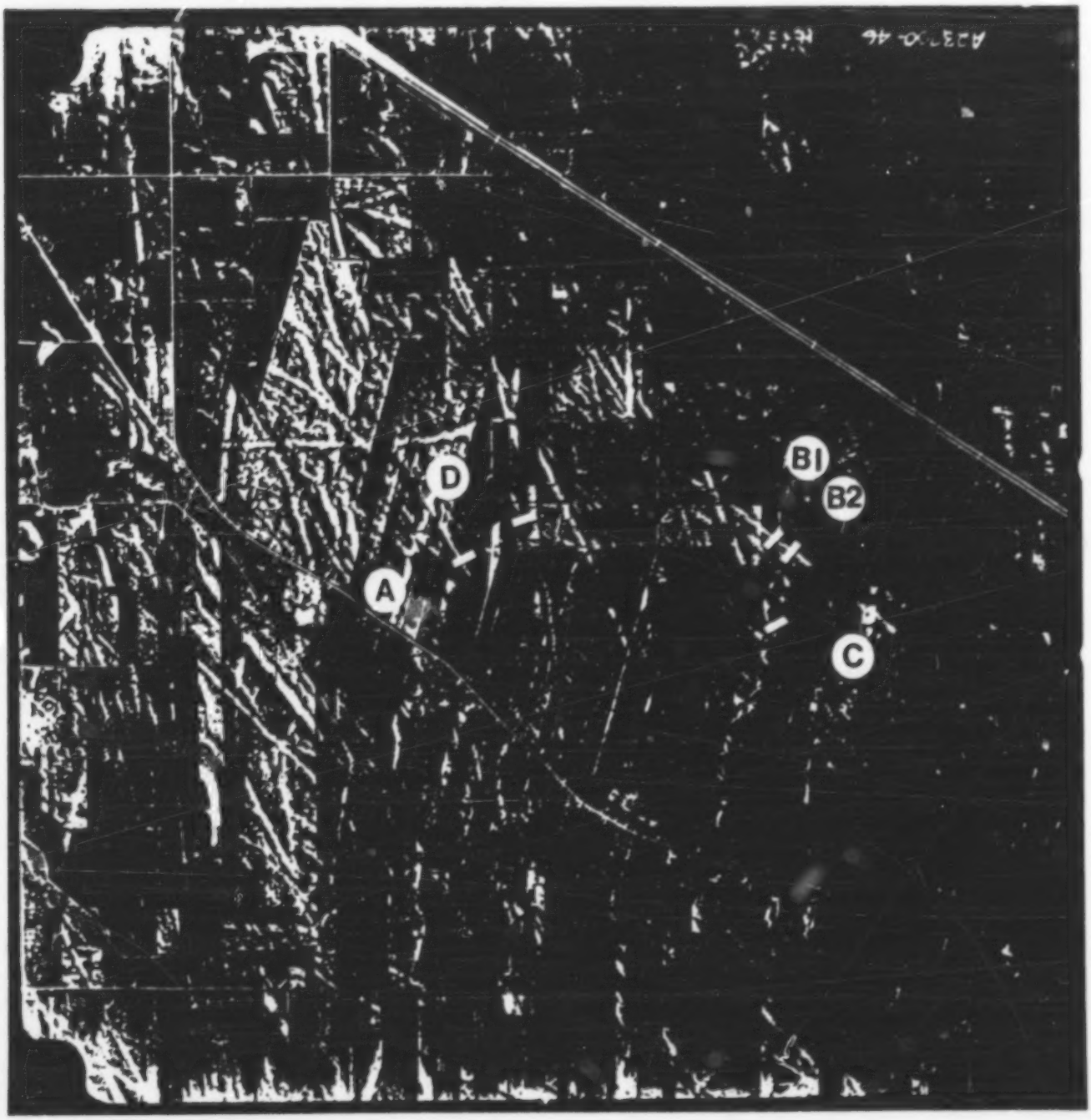

Figure 2. Aerial photograph of the study region southeast of Winnipeg. Iceberg scours show up as prominent white criss-crossing lines. Four scours, A-D, are described in this paper. The straight diagonal line in the upper right of the photograph is the Trans-Canada Highway.

Figure 3. View from the northeast berm looking towards the centre of the trough at scour B, trench 1, showing the incision surface (abrupt contact) separating dark, scoured massive sediments of the brown and grey clay, from overlying, well laminated silty clays of the tan-coloured unit. The incision surface dips away from the camera (white cards on the trench wall are spaced 1 m apart and define a horizontal line).

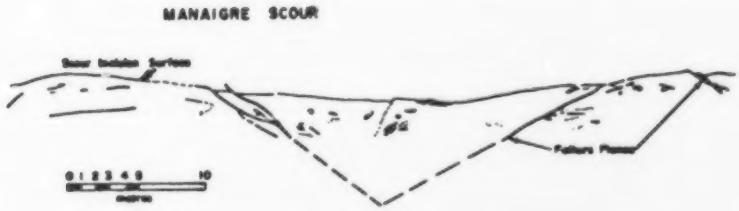

Figure 4a. Cross-section through scour B, trench 1, showing the scour incision surface, sub-scour faults (heavy lines) and deformed bedding. No vertical exaggeration.

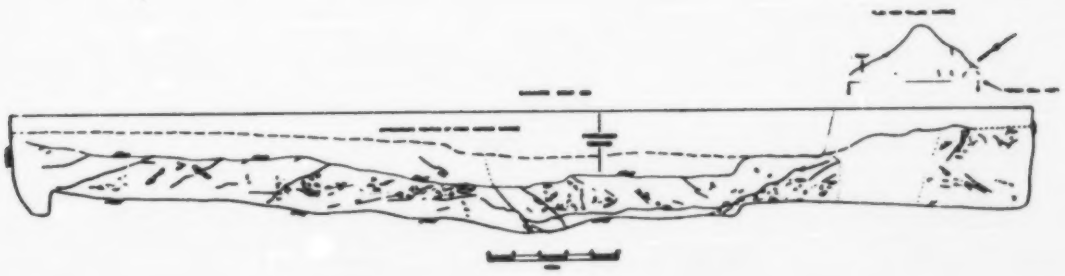

Figure 4b. Cross-section through scour B, trench 2, showing the scour incision surface, sub-scour faults (heavy lines) and deformed bedding. No vertical exaggeration.

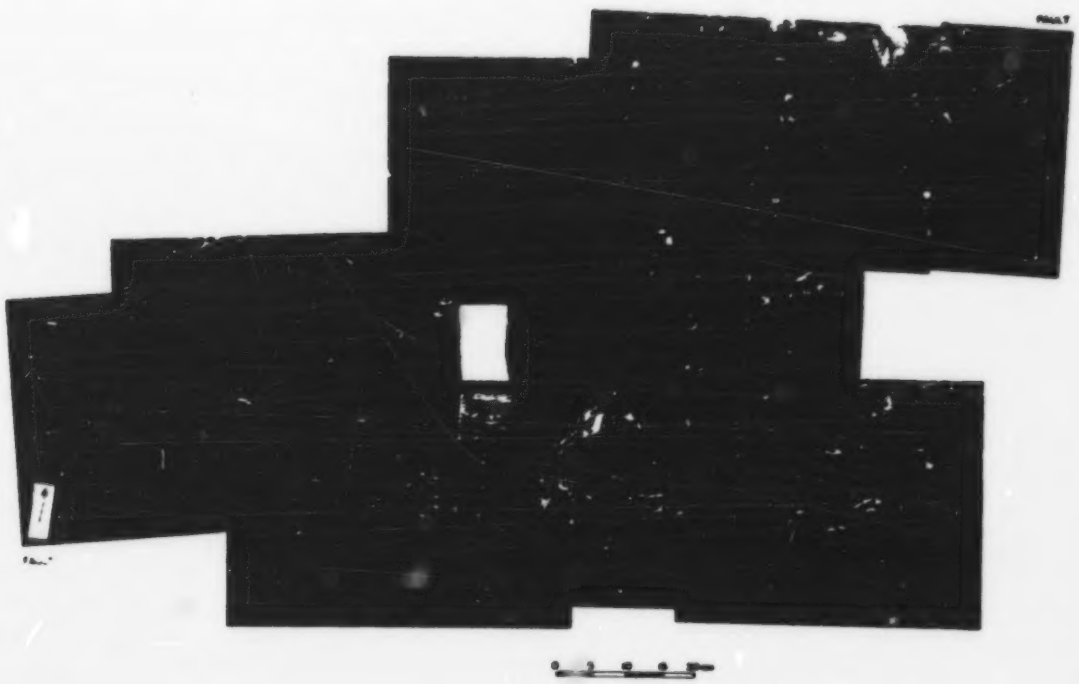

Figure 5. Low angle fault on the northeast side of scour B showing truncation of deformed bedding. Dip slip offset along this fault of at least 3.5 m can be inferred.

Figure 6. Photograph of typical fold geometries (defined by silt laminae) in the brown and grey clay below the incision surface of scour B, trench 1. Field of view is about 50 cm across.

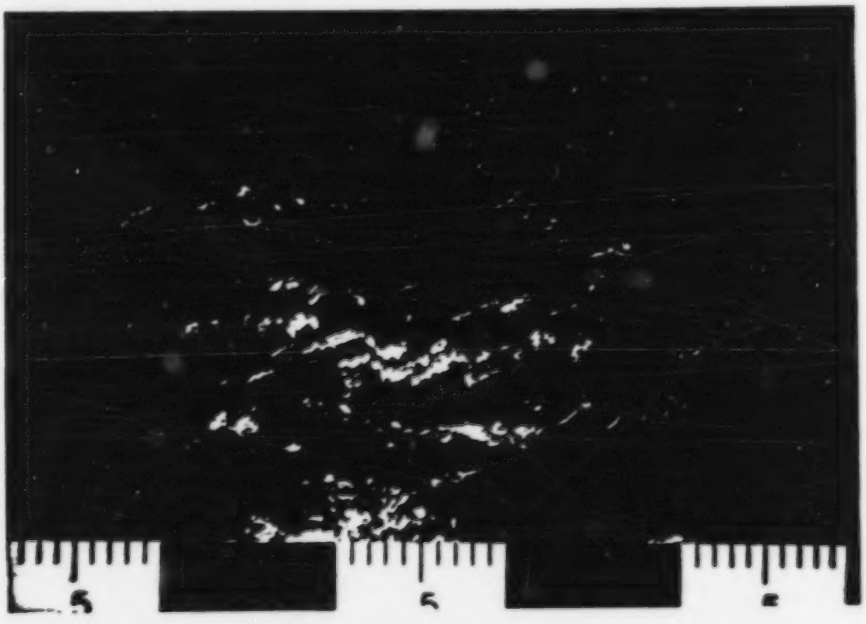

Figure 7. Fracture cleavage developed in part of a small scale open fold from the brown and grey clay below scour B. Note the larger displacements associated with a band in the centre of the photograph where several cleavage planes are bounded by regularly spaced (approx. 4 mm) slip planes defined by larger offsets (approx. 2 mm).

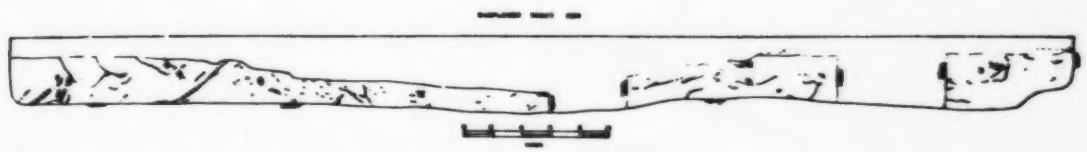

Figure 8. Cross-section through scour C. No vertical exaggeration.

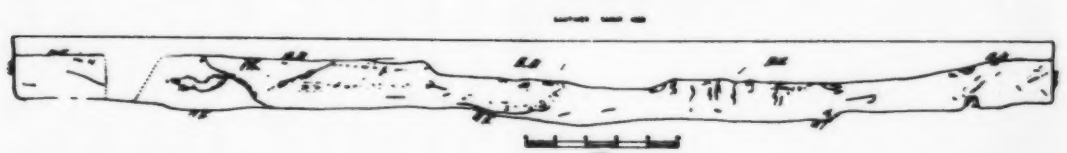

Figure 9. Cross-section through scour D. No vertical exaggeration.

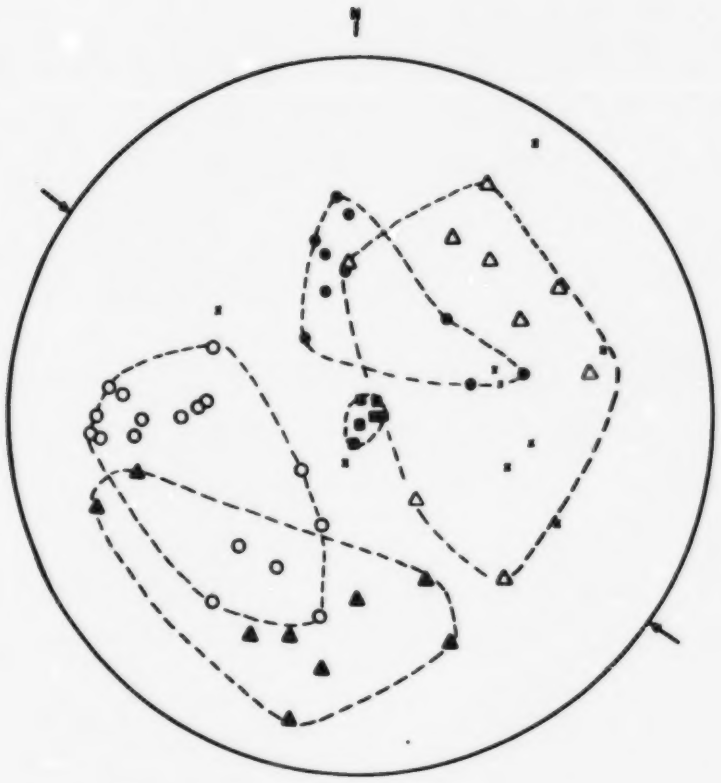
Low-angle fault (NE side of scour)
Low-angle fault Slickensides(NE side of scour)
Low-angle fault (SW side of scour)
Low-angle fault Slickensides (SW side of scour)
Horizontal faults
High-angle faults

Figure 10a. Stereonet of fault (plotted as poles to planes) and slickenside orientation, scour B, trench 1. Note how the low angle fault and associated slickenside orientations, plotted with respect to the side of the scour axis on which they occur, fall into distinct structural domains arranged symmetrically about the axis (the orientation of which is shown as two heavy black arrows). Sub-horizontal fault data for both sides of the scour are tightly clustered in the centre of the diagram. High angle fault orientations (measured only from the southwest side) are widely dispersed reflecting unconstrained failure.

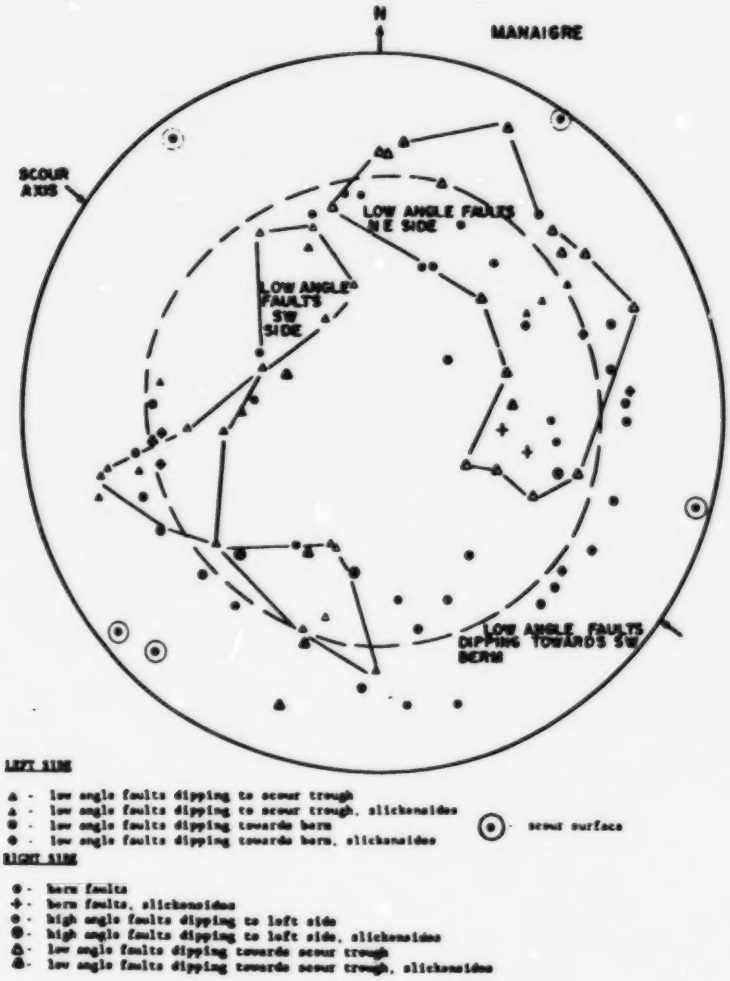
N
MANAIGRE
SCOUR AXIS
LOW ANGLE FAULTS NE SIDE
LOW ANGLE FAULTS SW SIDE
LOW ANGLE FAULTS DIPPING TOWARDS SW BERM
LEFT SIDE
- low angle faults dipping to scour trough
- low angle faults dipping to scour trough, slickensides
- low angle faults dipping towards berm
- low angle faults dipping towards berm, slickensides
- scour surface
RIGHT SIDE
- berm faults
- berm faults, slickensides
- high angle faults dipping to left side
- high angle faults dipping to left side, slickensides
- low angle faults dipping towards scour trough
- low angle faults dipping towards scour trough, slickensides

Figure 10b. Stereonet of fault (plotted as poles to planes) and slickenside data from scour B, trench 2.

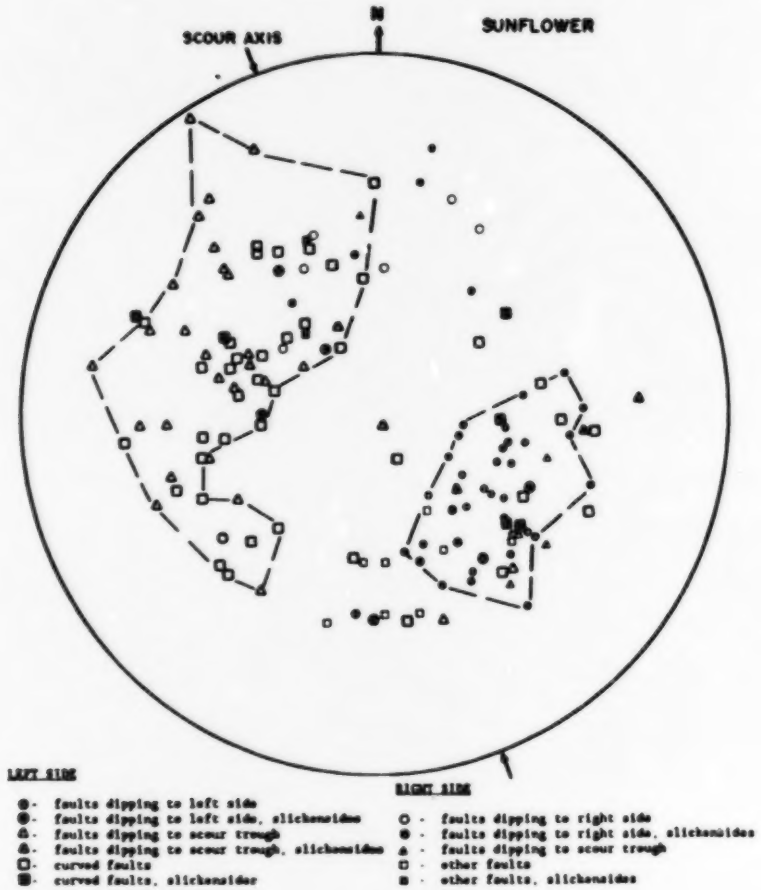

Figure 11. Stereonet of fault (plotted as poles to planes) and slickenside data from scour C.

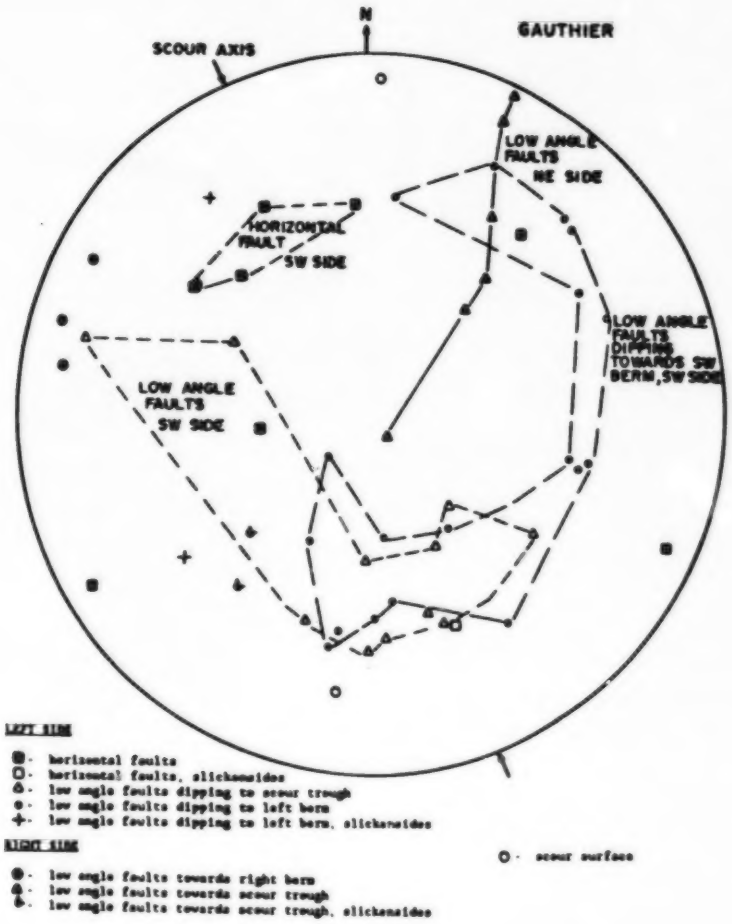
N
GAUTHIER
SCOUR AXIS
LOW ANGLE FAULTS NE SIDE
HORIZONTAL FAULT SW SIDE
LOW ANGLE FAULTS DIPPING TOWARDS SW BERM, SW SIDE
LOW ANGLE FAULTS SW SIDE
LEFT SIDE
- horizontal faults
- horizontal faults, slickensides
- low angle faults dipping to scour trough
- low angle faults dipping to left berm
- low angle faults dipping to left berm, slickensides
RIGHT SIDE
- low angle faults towards right berm
- low angle faults towards scour trough
- low angle faults towards scour trough, slickensides
- scour surface

Figure 12. Stereonet of fault (plotted as poles to planes) and slickenside data from scour D.

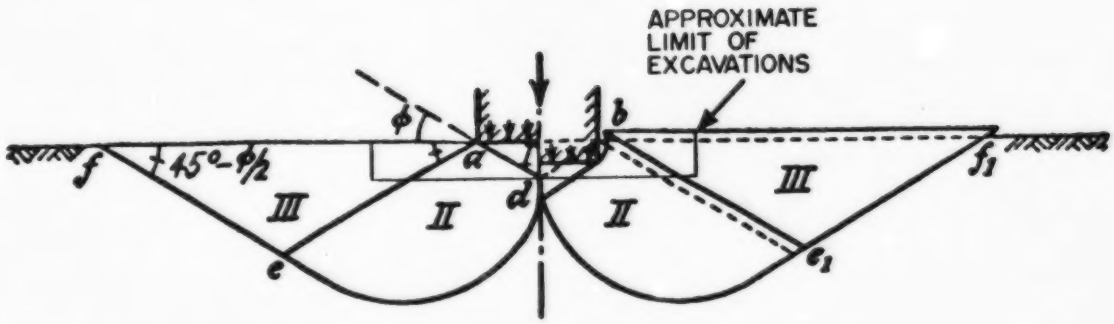

Figure 13. The kinematic model for two-dimensional shallow bearing capacity failure beneath a scouring keel (adapted from Terzaghi, 1959) as advanced by Poorooshasb et al. (1989). The triangular-shaped area (*I*) beneath the keel is the zone bounded by the low angle faults and the scour incision surface. A normal sense of fault motion is implied. Two zones (*II*) of radial shear, *ade* and bde_1, occur on either side of zone *I* and two passive Rankine zones (*III*) beyond. The approximate area represented by the excavations of scour B is shown. This interpretation implies the continuation of low angle faults to at least 6 m below the deepest part of the scour trough.